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Potential Applications of LRR-STAR Technology for GPM Mission

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Abstract

The Earth Science Division of NASA (Code Y) supports the development of advanced technology, including new aircraft and satellite instrumentation, under the Instrument Incubator Program (IIP). The IIP is administrated through the Earth Science Technology Office (ESTO) whose mandate includes helping guide new technology ideas up the development path for possible space flight opportunities. The Lightweight Rainfall Radiometer (LRR) project has been funded by ESTO to develop a prototype synthetic thinned array radiometer (STAR) for measuring precipitation in the cm-mm spectrum.

This paper describes the potential applications of a LRR-STAR instrument for the recently approved Global Precipitation Measurement (GPM) mission. [Another paper in this volume, provided by Professor Christopher Ruf and various of his colleague, describes the instrument design, engineering, calibration, and test program aspects of the LRR-STAR instrument.] The GPM mission will involve a constellation of 8-10 satellites, all of which will require some type of passive microwave radiometer taking measurements in various or all of the standard rain frequencies from 10.7 to 90 GHz. There are two possible entry points for LRR-STAR technology into the mission in the near term (given that certain strategic and/or fiscal conditions arise), and a strong possibility that this type of technology will displace the more conventional radiometer design which involves real-aperture scanning antennas, feedhorn arrays, and somewhat cumbersome calibration apparatus.

1. Introduction

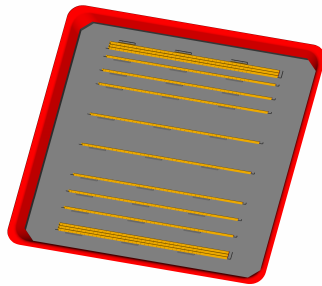
The NASA/NASDA sponsored Tropical Rainfall Measuring Mission (TRMM) demonstrated the value of a precipitation research program based on satellite measurements. The positive scientific impacts stemming from use of TRMM data for climatology and weather prediction have encouraged scientists involved with climate dynamics, meteorology, hydrology, and the global water and energy cycle to consider a new mission which would provide more frequent precipitation measurements on a global basis. In fact, at this juncture, the satellite precipitation community is strongly advocating a constellation-type rainfall mission to extend and expand the TRMM precipitation research program. In 1999, NASA/GSFC established a pre-formulation office to provide a careful examination of the requirements, organization, and programmatic support for an advanced rainfall mission that could overcome TRMM's basic shortcomings of inadequate sampling and restricted earth coverage. In 2001, NASA/Headquarters' Earth Science Division directed GSFC to begin advanced studies of the Global Precipitation Measurement (GPM) mission, a constellation type mission involving a fleet of satellite all capable of direct measurement of rainfall; see Shepherd et al. (2001). These studies were structured to facilitate an anticipated "approval-to-proceed" with formal formulation activities to be carried out in the future. In November 2001, Headquarters provided formal direction to GSFC to carry forward the new GPM mission.

Concurrent with the above activities, technology development efforts supporting the mission were initiated. Based on the 2nd round Instrument Incubator Program (IIP) competition, ESTO provided funding for JPL's PR-2 dual-frequency Doppler radar with polarization diversity as a possible 3rd generation radar system for GPM (Im and Smith, 1998; Im et al., 2000). ESTO also funded in both the 1st and 2nd rounds of the IIP, development of the GSFC Lightweight Rainfall Radiometer (LRR), a synthetic-thinned array radiometer (STAR) system; see Ruf et al. (1988, 2000). While NASA pursues the philosophy that the GPM mission will be implemented in a low-risk framework, these new technologies could be used in areas not critical to central mission success (e.g., flown as auxiliary instruments), and/or could be readied to replace current constellation instruments as needed and as a global precipitation observing system evolves.

The LRR-STAR design is a reduced risk approach for rainfall measurement because the instrument is free of moving parts, i.e., it does not need an antenna scan-drive assembly with mechanical failure points. By using interferometric measuring principles produced by spacing slotted waveguides at selected intervals across an aluminum antenna frame mounted on an aircraft or satellite perpendicular to the earth-pointing axis, in which each waveguide is equipped with its own receiver on the back plane, cross-track convolution images at desired frequencies and polarizations can be obtained from a rigid-mount payload. With this design, the parallax between waveguides provides the phase-shift interferogram information while the waveguide spacing covers all essential multiple-half wavelength modes of a transform image. Furthermore, by use of solid state MMIC receiver technology and ultra low power digital quadrature demodulators and cross correlators, it is possible to explore a technology path for rain measurement that involves a less expensive, lower weight, reduced power demand type of instrument, and one whose calibration stability is superior to conventional scan-type radiometers. The design allows for multiple channels and polarizations, while the antenna can be oriented in either a nadir-oriented cross-track configuration or a canted cross-track configuration to replicate either cross-track or conical scanning orientations typically used for conventional scanning

radiometers. Note the canting angle can be defined to produce equal-incidence viewing beams over the ± 45 degree field of the deconvoluted image, identical to the approach used for a standard conical scan radiometer system. Figure 1 provides a schematic illustration of the LRR-STAR instrument design.

Instrument Ground Plane



Electronics Back Plane

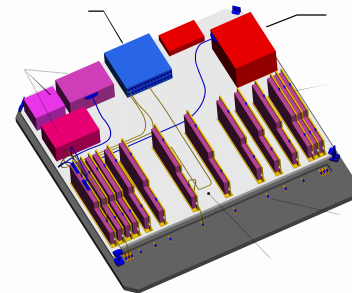


Figure 1: Instrument ground plane (left panel) containing 14 waveguides in which every multiple half-wavelength spacing is represented for producing horizontal convolution image at desired spatial resolution; electronics back plane (right panel) containing 14 receivers, power distribution unit, LO/noise and splitter box, analog I/O box, correlator unit, PC-104 stack, and waveguide attachments.

2. Science Agenda and Design of GPM Mission

From NASA's perspective, the GPM mission has three main scientific objectives recognizing that the research must focus on both: (a) measuring and retrieval, and (b) use of rain retrievals for improving predictions of climate, weather, and hydrometeorology, as well as for gaining a better understanding of the global water and energy cycle in general; see Smith et al. (2002) and Mehta et al. (2002). The specific scientific objectives are as follows: (1) improve climate predictions through progress in quantifying trends and space-time variations of rainfall and associated error bars in conjunction with improvements in achieving water budget closure from low to high latitudes -- plus focused GCM research on advanced understanding of the relationship between the triplicate of rain microphysics-latent heating-DSD properties and climate variations as mediated by accompanying accelerations of both atmospheric and surface branches of the global water cycle; (2) improve weather predictions through accurate, precise, frequent and globally distributed measurements of instantaneous rainrate and latent heat release -- plus focused research on more advanced NWP techniques in satellite precipitation assimilation and error characterization of precipitation retrievals; and (3) improve hydrological predictions through frequent sampling and complete continental coverage of high resolution precipitation measurements including snowfall -- plus focused research on more innovative designs in hydrometeorological modeling emphasizing hazardous flood forecasting, seasonal draught-flood outlooks, and fresh water resources prediction. These objectives synthesize into the mission agenda various overarching science goals articulated in the decadal science strategy of Code Y's Earth Science Enterprise (ESE); see Asrar et al. (2001).

With the above scientific objectives in mind, NASA in collaboration with NASDA have crafted a preliminary mission concept. This concept calls for the development of a core satellite, somewhat akin to TRMM, but with instrumentation better suited to perform detailed measurements of cloud microphysics, structure, and dynamics, and ultimately precipitation processes. The essential rain measuring instrumentation on the core satellite follows that used by TRMM, but with improved sensing capabilities. The two primary instruments consist of: (1) a

dual-frequency precipitation radar, referred to as the DPR (designed by the Communication Research laboratory in Japan) for measuring reflectivities at Ku- and Ka-bands (13.6 & 35 GHz) with sensitivities of 17 dBz and 11 dBz, respectively, and vertical resolutions of 250 m at Ku-band and 250/500 m switchable at Ka-band depending on its low/high sensitivity mode setting; and (2) a multichannel, conical-scanning, passive microwave radiometer incorporating the same frequencies and polarization selections used by TRMM (with the possibility of additional frequencies at 150 and 183 GHz) but with an antenna size twice that of TRMM (~1.2 m).

An additional constellation of eight (8) or more satellites carrying various types of passive microwave radiometers and with the rain frequencies is planned to augment the measurements made by the core satellite, essentially to provide frequent, global coverage. The constellation will include satellites developed and operated by NASA and other United States government agencies, as well as by various international partners. The constellation will be based on a combination of operational weather satellites and environmental research satellites developed for other programs, and various satellites solely dedicated to use in the GPM constellation. By approaching the measuring problem in this fashion, the GPM mission will be able to produce globally complete rainfall datasets with a temporal resolution at any given location of at least 3 hours. An illustration of the design of GPM's satellite fleet (core & constellation) is shown in Figure 2.

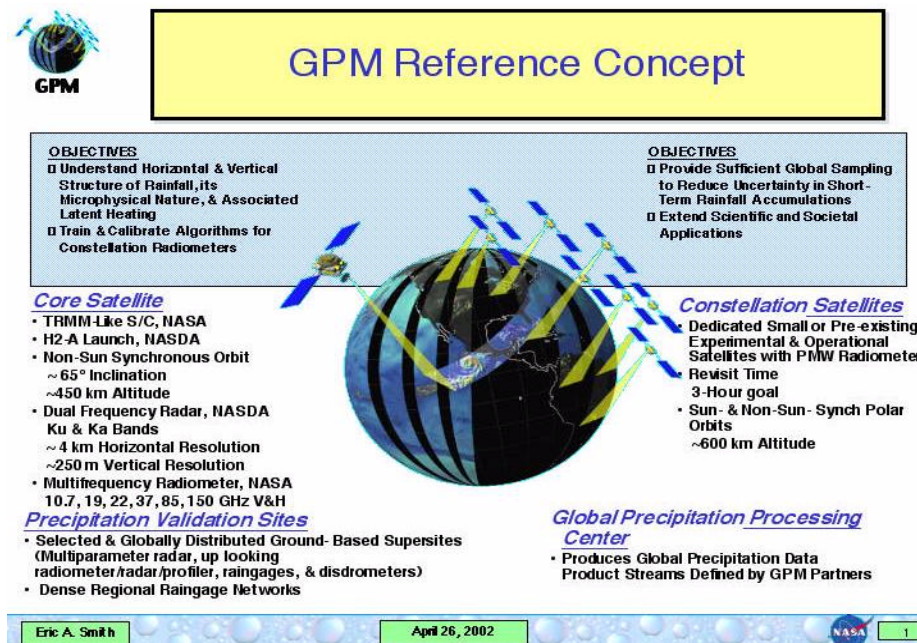


Figure 2: Notional GPM mission concept.

3. Potential Near-Term Applications of LRR in GPM Mission

In order to achieve a program goal of frequent rainfall measurements on a global basis, up to eight constellation satellites in addition to the core satellite will be required. During the GPM mission era, which is now scheduled to commence in the late 2007 time frame, rainfall measurements will be available from microwave radiometers on operational weather satellites such as DMSP and NPOESS-Lite, and most likely China's FY-3 LEO satellite series, as well as from planned environmental research satellites including NASDA's GCOM-B1 and

ISRO/CNES's Megha Tropiques satellites. By using these satellites as a foundation for developing a constellation, it is possible for GPM to achieve its global measurement goal of 3-hourly sampling with the addition of 2-3 additional constellation spacecraft. Currently NASA and ESA are each planning to develop one dedicated constellation satellite (with each carrying a rain radiometer), to ensure the completeness of the GPM fleet.

3.1 Reduced Cost Version for NASA Constellation Spacecraft

One potential application for a LRR-STAR instrument would be as a single instrument deployment on small, low power constellation spacecraft. In NASA's current plan for developing a constellation spacecraft, in addition to their contributions to the core satellite, i.e., NASA provides the core satellite bus and conical-scanning radiometer (the GMI) while NASDA provides the DPR and launch service (on a H2A rocket), they are planning to purchase a 2nd copy of an industry provided GMI for use on a RSDO-compliant satellite bus. Because of potential cost restrictions and accommodation difficulties with this approach, a simpler and less costly approach would be to use a LRR-STAR on an even smaller bus and commence with the initial assessment of the viability of this type of radiometer design.

The ESTO-funded IIP project under which the aircraft instrument prototype is being developed has produced a single frequency X-band instrument which will be ground- and aircraft-tested in calendar-year 2003 to determine how well it achieves its expected performance in measuring and calibration versatility. An summary of the prototype project is presented in Figure 3a. During the aircraft testing campaign, the prototype instrument will be aligned with GSFC's AESMIR radiometer, a conventional scanning system which includes 10.7 GHz channels, to aid in understanding its performance capabilities; see Figure 3b. An important consideration in proceeding from the prototype single frequency design to a space-qualified design that would have the needed attributes for retrieving precipitation in the context of the GPM mission, is the requirement for multiple frequencies and possibly multiple polarizations. This would imply the need for perhaps at least four (4) channels on a stand-alone spacecraft version of the LRR-STAR.

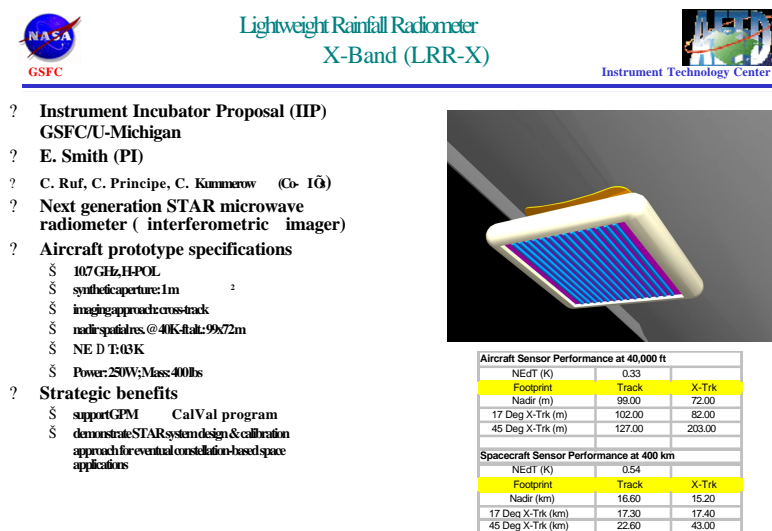


Figure 3a: IIP project overview of prototype LRR-STAR single channel X-band (10.7 GHz) instrument including schematic of aircraft mounting configuration; instrument specifications for aircraft and spacecraft versions indicated in tables.

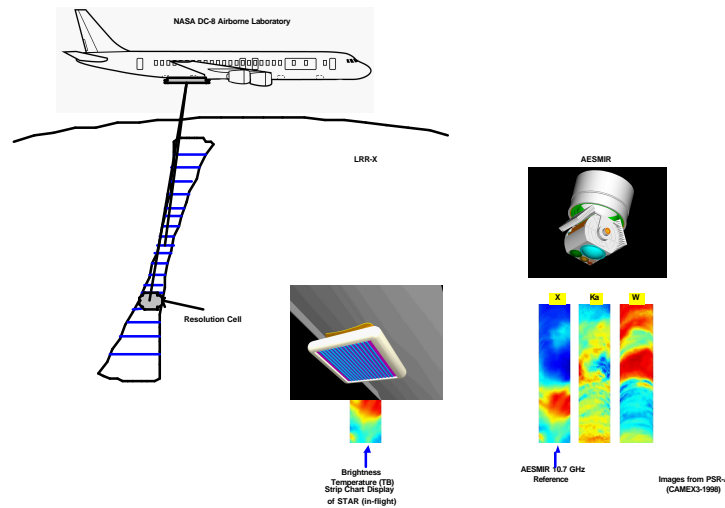


Figure 3b: Schematic of paired deployment of prototype LRR-STAR X-band radiometer with GSFC's tiltable cross-track scanning AESMIR radiometer.

3.2 Dual Frequency Version of LRR-STAR Bore-Sighted with Core Satellite's DPR

Perhaps a more compelling application of the new LRR-STAR technology would be to fly a nadir oriented version on the GPM core satellite in a deployment configuration bore-sighted with the DPR system, matching both frequencies of the DPR (i.e., 14 and 35 GHz – identically Ku- and Ka-bands) and with the beam apertures configured to match those of the Ku-band radar (to which the DPR Ka-band radar is also matched). Schematic illustrations of this type of configuration and its specifications are shown in Figures 4a-b. With each instrument measuring identical atmospheric volumes at both frequencies, it would then be possible to conduct a number of valuable experiments, heretofore not possible with the TRMM satellite whose radar (PR) is cross-tracked scanned through nadir while its radiometer (TMI) is conically scanned to obtain invariant earth incidence viewing across its full scan path. [With the TRMM satellite, the single frequency Ka-band radar beams are obtained approximately one minute later than the radiometer beams, while the two instrument's beam patterns themselves are not contiguous because of both differences in viewing geometry and in aperture dimensions.] A full-up design study conducted at GSFC's instrument simulation analysis laboratory has already demonstrated the feasibility of the 2-frequency design, and has estimates of the engineering tolerances and software tools needed to ensure satisfactory volume matching; see Figure 4c.

The foremost experiment deserving attention would involve using the radiometer measurements to estimate total path attenuation, also referred to as path-integrated attenuation (PIA), along the same beam paths probed by the two radar transmitters. These estimates would be independent of those from the radar which require the application of the surface reflectance technique (SRT) and thus are dependent on reflectivity (backscatter) information; Meneghini et al. (2000). Thus, in principle, the radiometer estimates are less noisy and cover a greater dynamic range than

afforded by radar estimates, including extending well down into the medium and lighter rainrates where most of the rain accumulation spectrum is located; see Wilheit and Everett (2001).

Given this capability, two further experiments would be in order. The first of these would seek refinement of the combined radar-radiometer algorithm technique, as defined by Smith et al. (1997) and Haddad et al. (1997), in which the independent PIA estimates would tighten the constraints on the retrieved profile as cast in a Bayesian inversion problem. The final experiment would involve use of the improved characterization of the bulk microphysics provided by the volume-matched radar-radiometer measurements as a means to seek physically-based calibrations of rainrates retrieved from all conically scanning radiometers on core and constellation spacecraft.

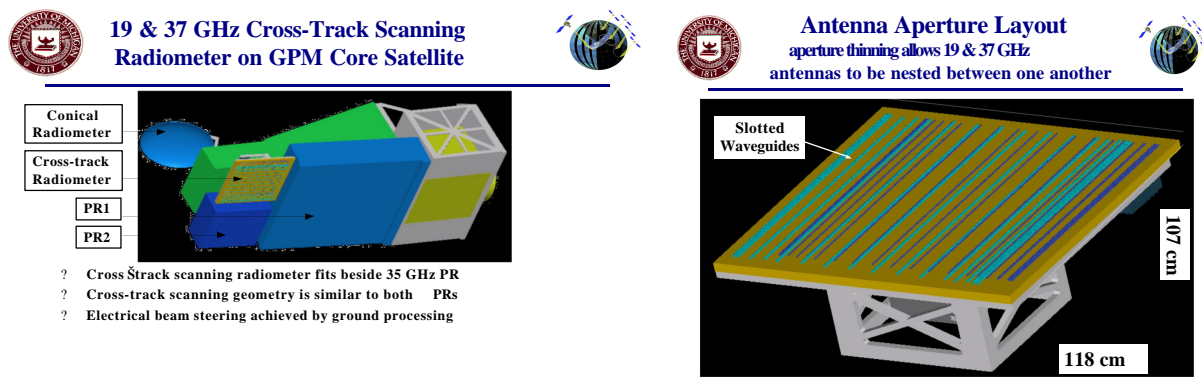


Figure 4a: Left panel presents schematic of dual-frequency 14-35 GHz LRR-STAR system, bore-sighted with GPM core satellite's DPR, while right panel presents slotted waveguide design in which two (2) sets of 14-member thinned waveguide arrays are intermeshed across single antenna frame.

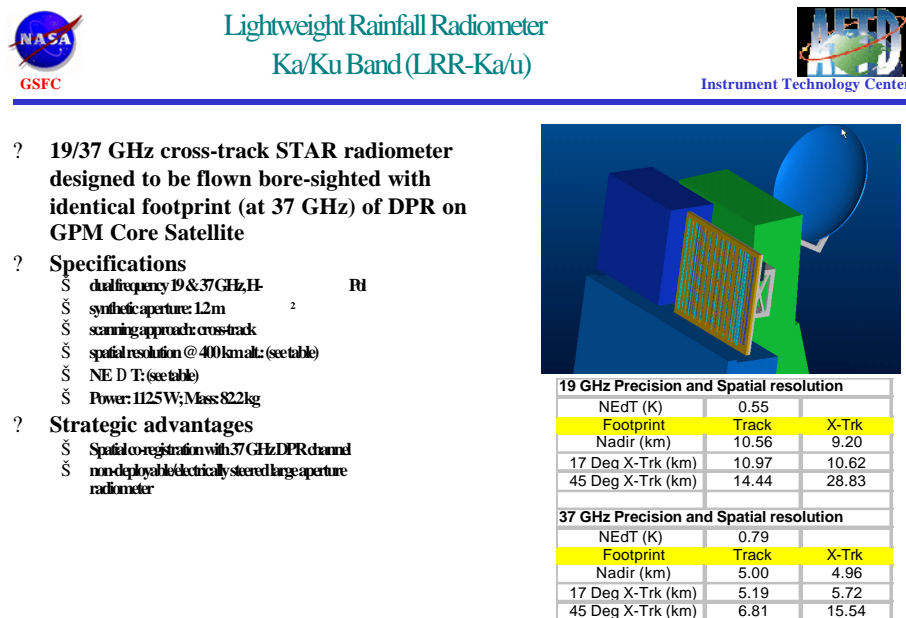
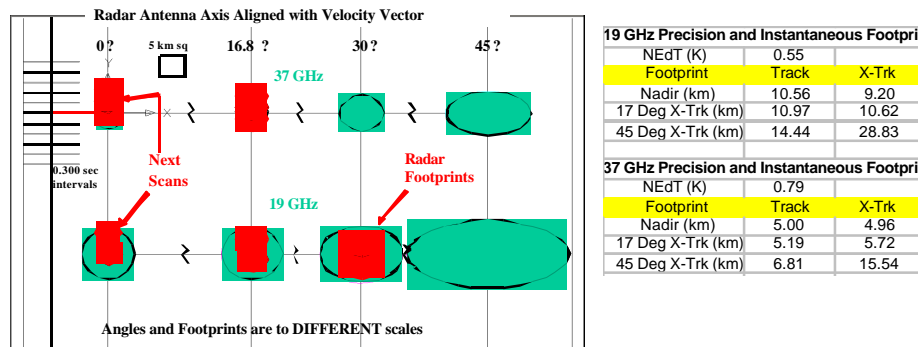


Figure 4b: Overview of dual frequency 14-35 GHz LRR-STAR system including schematic of instrument location on GPM core satellite assuming bore-sighted configuration with respect to DPR.



- Instantaneous footprints shown above.
- DPR and LRR-37 GHz footprints matched within ~200 m by ground processing.

Figure 4c: Schematic of footprint layout between dual frequency 14-35 GHz LRR-STAR system and DPR system for bore-sighted configuration on GPM core satellite.

4. Conclusions

The development of an advanced technology for fabricating multichannel, passive microwave rain radiometers is based on the use of: (1) interferometric principles; (2) slotted waveguide, thinned array, compact antenna design; and (3) digital deconvolution circuits. These design approaches, some of which were adapted from techniques first developed by radio astronomers almost 50 years ago, promise to reduce costs, lower weight and power requirements, mitigate risks of mechanical failure, and improve calibration stability. Here we explore various possible immediate benefits of using LRR-STAR technology within the GPM mission. Whereas one mandate of the GPM mission invoked by NASA/Headquarters is to proceed with mission development without requiring use of untested technology or allowing the encounter of serious technology risks, it has been noted here that there are auxiliary applications of the LRR-STAR radiometer technology that could produce significant mission benefits without jeopardizing the mission's central aims.

One such application is using a 4 or more channel version of the LRR-STAR as the main instrument on a constellation spacecraft deployed in a minimal cost-configuration design. The main benefits here would be the stimulation of a small-dedicated constellation spacecraft development program that NASA and its fellow space agencies in other countries could gravitate towards for use in a next generation global precipitation observing system. It would be helpful to gain early experience concerning the pros and cons of shifting to this approach, because there are so many compelling features of this technology vis-à-vis conventional microwave radiometer technology which requires scan mirror assemblies, feed horn arrays, and relatively awkward calibration apparatus needed for obtaining stabilized cold and warm load views.

Another application uses a 2-frequency LRR-STAR (19 & 37 GHz) deployed in a bore-sighted and beam-matched configuration in conjunction with the core satellite's 2-frequency precipitation radar. This has multiple scientific benefits, the most important being: (1) enabling improved rainfall retrieval through combined radiometer-radar algorithms, exploiting the

improvements insofar as reduced uncertainties and greater dynamic range in acquiring path integrated attenuation from the radiometer channels vis-à-vis just information available from radar reflectivity-based surface reference technique estimates; (2) allowing better characterization of the microphysics of precipitating clouds insofar as bulk drop size distribution properties; and (3) providing agility to independently calibrate the conical scan radiometer algorithms on the core and constellation satellites without suffering degradation due to space-time mismatches in the measuring volumes.

The purpose of this paper is to provoke thinking and debate concerning the possible use of the LRR-STAR technology during the course of the GPM mission, not to insist that this technology path is essential for the success of the mission. However, since it appears that there are possible plus-ups to a rainfall mission's effectiveness by incorporating the LRR-STAR approach but without undermining the low risk technology paths required for central mission elements, it seems wise that the thinking and debate should turn on the practical question of when and where this technology should be inserted into an actual space-based measuring program.

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